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955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

B71 10009

date: October 15, 1971

to: Distribution

from: W. Levidow

subject: CMG Control of Skylab Night-Time Z-Local-Vertical Passes - Case 620

ABSTRACT

A 120° Z-Local-Vertical (ZLV) pass centered at midnight can be executed without TACS assistance by starting the maneuver to ZLV and ending the maneuver from ZLV at a point in orbit slightly before noon. By this tactic, the change in momentum during the maneuvers can be made to offset the change during ZLV, resulting in nearly zero net change.

A full orbit in ZLV results in a CMG momentum change of about -6120 ft-lb-sec along the vehicle Y axis. Although the momentum variation during the orbit can be accommodated without CMG saturation, the value of the final momentum state prevents flying a subsequent ZLV or solar inertial orbit without TACS assistance.

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MEMORANDUM FOR FILE

Introduction

This memorandum presents the capability of the Control Moment Gyros (CMGs) to control the Skylab in a 120° Z-Local-Vertical (ZLV) pass, centered about orbital midnight, without the need for TACS assistance. During the pass the spacecraft is oriented with the X axis directed along the velocity vector and the -Z axis directed along the local vertical toward earth. The CMGs provide the torque for maneuvering the vehicle from solar inertial (SI) attitude and for holding the ZLV attitude.

To avoid the need for TACS assistance, the CMGs must provide this torque without reaching momentum saturation. In addition, the CMG momentum state on re-attaining SI must be such that a normal SI and night-time momentum dump orbit can subsequently be flown without CMG saturation.

Maneuver Procedure

In executing the maneuver to ZLV, the vehicle, which is in SI at η_1, Fig. 1, is given a maneuver rotational rate $\underline{\omega}_1$ such that it attains ZLV when it arrives at the start of the ZLV pass at η_{LV1}. At this point the maneuver rate is removed and the orbital rate $\underline{\omega}_0$ is imparted to the vehicle. The ZLV attitude is held until η_{LV2}, where the orbital rate is removed and the maneuver rate $\underline{\omega}_2$ applied so that the vehicle attains SI at η_2. Here the maneuver rate is removed and the vehicle remains in SI.

CMG Momentum Change Requirements

During the execution of the maneuvers and the ZLV pass, the significant CMG momentum variations occur in a direction normal to the orbital plane. Although the other components contribute somewhat to CMG saturation, only this normal component is considered here. For simplicity, the vehicle Z axis is considered to lie in the orbital plane (β*=0°) during SI. Therefore this normal momentum component lies along the vehicle Y axis.

The study can be extended to cover other values of β. However, a computer simulation with SI attitudes of $\beta=\pm 50°$ yielded results not significantly different from those presented here.

The CMG momentum change, $\Delta \underline{H}$, between η_1 and η_2 is given by

$$\Delta \underline{H} = \Sigma \underline{H}_\omega + \int_{\eta_1}^{\eta_2} \underline{T}_{gg} \, dt - \int_{\eta_1}^{\eta_2} \underline{\omega} \times I \underline{\omega} \, dt \qquad (1)$$

where:

$\Sigma \underline{H}_\omega$ = sum of CMG momentum changes required to impart proper angular velocity changes to the vehicle

$\underline{T}_{gg}$ = gravity gradient torque

$\underline{\omega}$ = vehicle angular velocity

I** = vehicle body axis inertia matrix

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*Angle of the earth-sun line above the orbital plane.

**The Skylab OA considered here corresponds to that of a 196,000 lb launch vehicle control weight and has the following estimated inertia properties.

$$I = \begin{bmatrix} 737000 & -9544 & -291000 \\ -9544 & 4712000 & -24250 \\ -291,000 & -24250 & 4666,000 \end{bmatrix} \text{slug-ft}^2$$

A. $\underline{\omega} \times I\underline{\omega}$ Term

Since the vehicle rotation is about the Y axis during both the maneuvers and the pass, the Y axis component of $\underline{\omega} \times I\underline{\omega}$ is zero and the last term of Eq. 1 can be discarded.

B. Gravity Gradient Term

The Y axis momentum change due to gravity gradient torque can be separated into three components: that during the maneuver $\underline{\omega}_1$ to ZLV (H_1), that during the ZLV pass (H_{LV}), and that during the maneuver $\underline{\omega}_2$ back to SI (H_2).

During ZLV the misalignment between the body and principal axes causes a constant Y axis gravity gradient torque. The change in momentum is given by

$$H_{LV} = -3\,\omega_0^2\, I_{XZ}\, t \text{ ft-lb-sec} \tag{2}$$

where

ω_0 = orbital rate, radians/sec

I_{XZ} = element of the inertia matrix I, slug-ft^2

t = time in ZLV attitude, seconds

For a 120° pass at 135 nm altitude, H_{LV} = -2040 ft-lb-sec.

It is of interest to note that if the vehicle is pitched θ° about the Y axis during the ZLV pass, then

$$H_{LV} = 3\omega_0^{\,2} t[\frac{S2\theta}{2}(I_{ZZ} - I_{XX}) - C2\theta\, I_{XZ}]\text{ft-lb-sec} \tag{3}$$

If

$$\theta = \frac{1}{2}\tan^{-1}[\frac{2I_{XZ}}{I_{ZZ}-I_{XX}}] \tag{4}$$

then H_{LV} = 0 and there is no momentum change along the Y axis. For the vehicle considered here, θ = 4.21° for H_{LV} = 0.

During the maneuver $\underline{\omega}_1$ from η_1 to η_{LV1} the pitch angle and hence the gravity gradient torque varies with time. For $0<\eta_{LV1}<\pi$, the CMG momentum change is given by

$$H_1 = \frac{3\omega_0}{2}\frac{(\eta_{LV1}-\eta_1)}{\eta_1}\left[\frac{(I_{ZZ}-I_{XX})}{2}(c2\eta_1-1)-I_{XZ}s2\eta_1\right]\text{ft-lb-sec} \qquad (5)$$

During the maneuver $\underline{\omega}_2$ from η_{LV2} to η_2 (for $\pi<\eta_{LV2}<2\pi$)

$$H_2 = \frac{3\omega_0}{2}\frac{(\eta_2-\eta_{LV2})}{(2\pi-\eta_2)}\left[\frac{(I_{ZZ}-I_{XX})}{2}(1-c2\eta_2)+I_{XZ}s2\eta_2\right]\text{ft-lb-sec} \qquad (6)$$

C. Angular Velocity Change Term

In providing torque for the angular velocity changes the CMGs undergo the following Y axis momentum changes.

Orbital Position	Momentum Change	Event
η_1	$H_{\omega 1} = -I\underline{\omega}_1 \cdot \underline{u}$	Accelerate to maneuver rate $\underline{\omega}_1$
η_{LV1}	$-H_{\omega 1}$ $H_{\omega 0} = -I\underline{\omega}_0 \cdot \underline{u}$	decelerate to zero rate accelerate to orbital rate $\underline{\omega}_0$
η_{LV2}	$-H_{\omega 0}$ $H_{\omega 2} = -I\underline{\omega}_2 \cdot \underline{u}$	decelerate to zero rate accelerate to maneuver rate $\underline{\omega}_2$
η_2	$-H_{\omega 2}$	decelerate to zero rate

where: $\underline{u}$ = unit vector along vehicle Y axis

$\underline{\omega}_0$ = orbital rate

Note: $H_{\omega 0}$ equals about -5300 ft-lb-sec.

$H_{\omega 1}$ and $H_{\omega 2}$ are proportional to the maneuver angular velocities $\underline{\omega}_1$ and $\underline{\omega}_2$ which in turn depend upon the required vehicle rotation angle between SI and ZLV and the time in orbit allotted for the maneuver. The rotation angle in each case is the orbital angle ($\leq\pi$) between η_{LV1} or η_{LV2} and orbital noon. For the 120° pass centered at midnight, both rotation angles are 120°. For a 120° pass centered at noon, both are 60°. For a pass starting at midnight the first maneuver rotation angle is 180° whereas for a pass starting at noon it is zero. The larger the rotation angle, the greater the required maneuver time in order to keep $\underline{\omega}_1$, $\underline{\omega}_2$, and the CMG momentum changes within reasonable limits.

CMG Momentum Constraints

The CMG momentum variation normal to the orbital plane is about $\pm$4200 ft-lb-sec during a typical SI (including night-time dump) orbit. By means of CMG momentum biasing, this variation can be shifted to one extreme of the $\pm$6000* ft-lb-sec 3 CMG saturation limits in anticipation of the ZLV pass. This allows the pass to cause a maximum difference of 3600 ft-lb-sec (measured before and after the pass at the same position in orbit), shifting the SI variation to the other extreme. During the pass the CMG momentum variations must also be contained within the $\pm$6000 ft-lb-sec limits.

Depending upon the momentum change caused by the ZLV pass, several SI orbits may be necessary to rebias (by night-time dumping) in preparation for the next ZLV pass.

ZLV Pass Strategies

If $\eta_1 = 0$ and $\eta_2 = 2\pi$, then $\underline{\omega}_1 = \underline{\omega}_0 = \underline{\omega}_2$ (for $\beta = 0°$), the vehicle is effectively in ZLV for the whole orbit, and H_{LV}= -2040 x 3. Angular velocity changes are required at η_1 and η_2 but not at η_{LV1} nor η_{LV2} because $H_{\omega 1} = H_{\omega 0} = H_{\omega 2}$. The Y axis momentum profile is shown in Fig. 2a. Although the maximum momentum variation (5300 + 6120) during the ZLV orbit can be contained within the $\pm$6000 limits, the orbital net momentum change of 6120 exceeds the 3600 limit. Hence the CMGs will saturate on the following SI orbit and TACS propellant will be required.

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*Estimated Y axis limits in the presence of typical X and Z momentum variations.

As previously mentioned, if the spacecraft were pitched about 4.2° around Y during ZLV, then $H_{LV} = 0$. In this attitude the CMG momenta before and after each pass are identical, and from a control standpoint many successive passes could be made without the necessity of rebiasing by momentum dumping between passes.

The effect of starting and ending the maneuver at positions other than orbital noon can be explored by evaluating Eqs. 5 and 6 as a function of η_1 and η_2 for a 120° pass centered at midnight. The results are shown in Table 1.

Table 1

η_1 (deg.)	H_1 (ft-lb-sec)	η_2 (deg.)	H_2 (ft-lb-sec)
-15	1676	345	1380
-10	413	350	350
- 5	- 867	355	- 800
0 (Noon)	-2040	360 (Noon)	-2040
5	-3100	365	-3370

Clearly it is advantageous to start the first maneuver and end the second maneuver before noon. In this manner the positive momentum changes during the maneuvers can offset the -2040 ft-lb-sec momentum drop during ZLV. Starting the first maneuver after noon only worsens the results of Fig. 2a.

Fig. 2b shows the Y axis momentum profile for $\eta_1 = -14°$ and $\eta_2 = 346°$ for a 120° ZLV pass centered at midnight. At equivalent points in orbit before and after the maneuvers (η_1 and η_2, for example) the momenta are almost equal. This type ZLV orbit can be executed consecutively many times without reaching CMG saturation and still have a favorable momentum state for a subsequent SI orbit.

ZLV passes offset from midnight can also be planned advantageously by using Eqs. 5 and 6 as an aid in selecting η_1 and η_2.

Conclusions

A full orbit ZLV pass starting and ending at noon causes a predominant CMG momentum change of about -6120 ft-lb-sec along the Y axis. This is due to a constant gravity gradient torque resulting from misalignment of the body and principal axes. Although the momentum variation during the orbit is within the 3 CMG saturation limits, the final momentum state is such that a subsequent ZLV or SI orbit cannot be flown without CMG saturation.

If the Skylab flies in ZLV with a constant pitch angle of about 4.2°, then the Y axis momentum change is zero and many successive orbits in ZLV can be flown without reaching saturation.

A 120° ZLV pass centered at midnight can be executed without a net change of Y axis momentum over the orbit by starting and ending the maneuvers to and from ZLV at a point in orbit slightly before noon. By this scheme the decrease in Y axis momentum during ZLV can be offset by increases during the maneuvers. No TACS assistance is required during this orbit nor during a subsequent ZLV or SI orbit.

These conclusions on TACS requirements are based solely on momentum change considerations. Inability of a CMG to provide the required momentum changes because of gimbal stop restraints may necessitate TACS assistance even though 3 CMG momentum saturation has not been reached.

W. Levidow

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Attachments

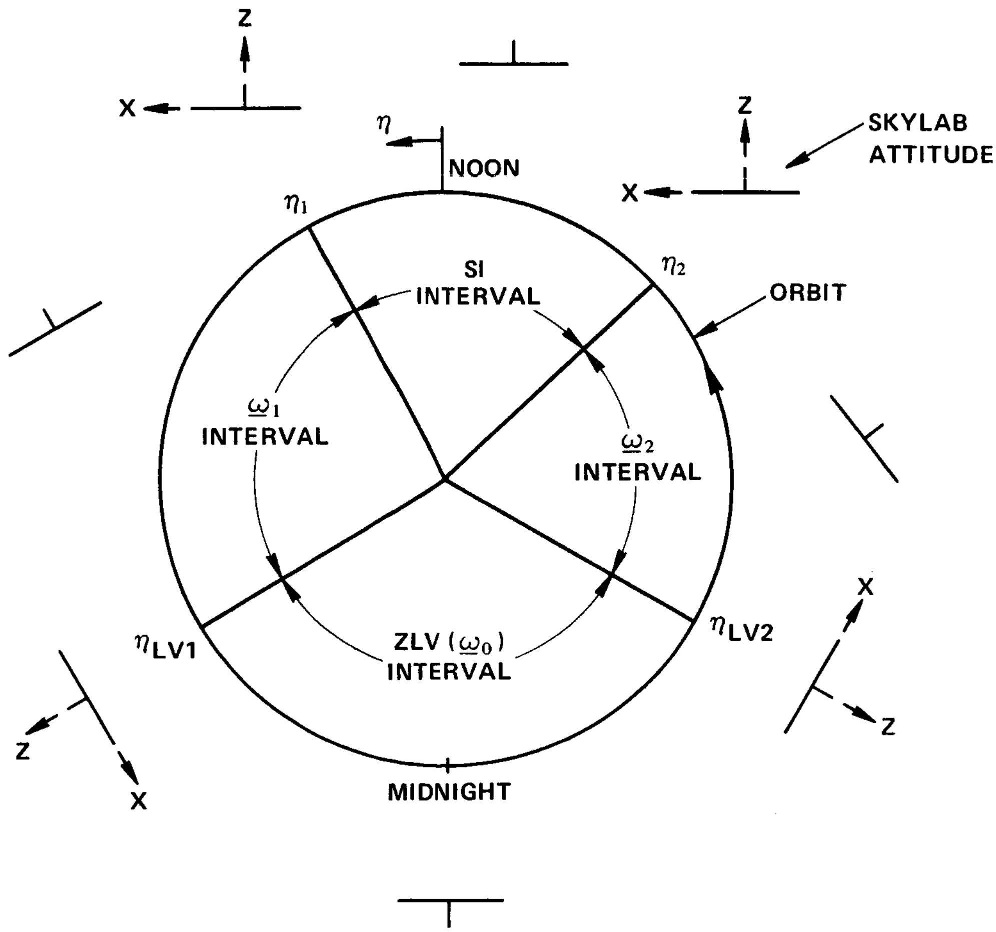

FIGURE 1 - ZLV MANEUVER GEOMETRY

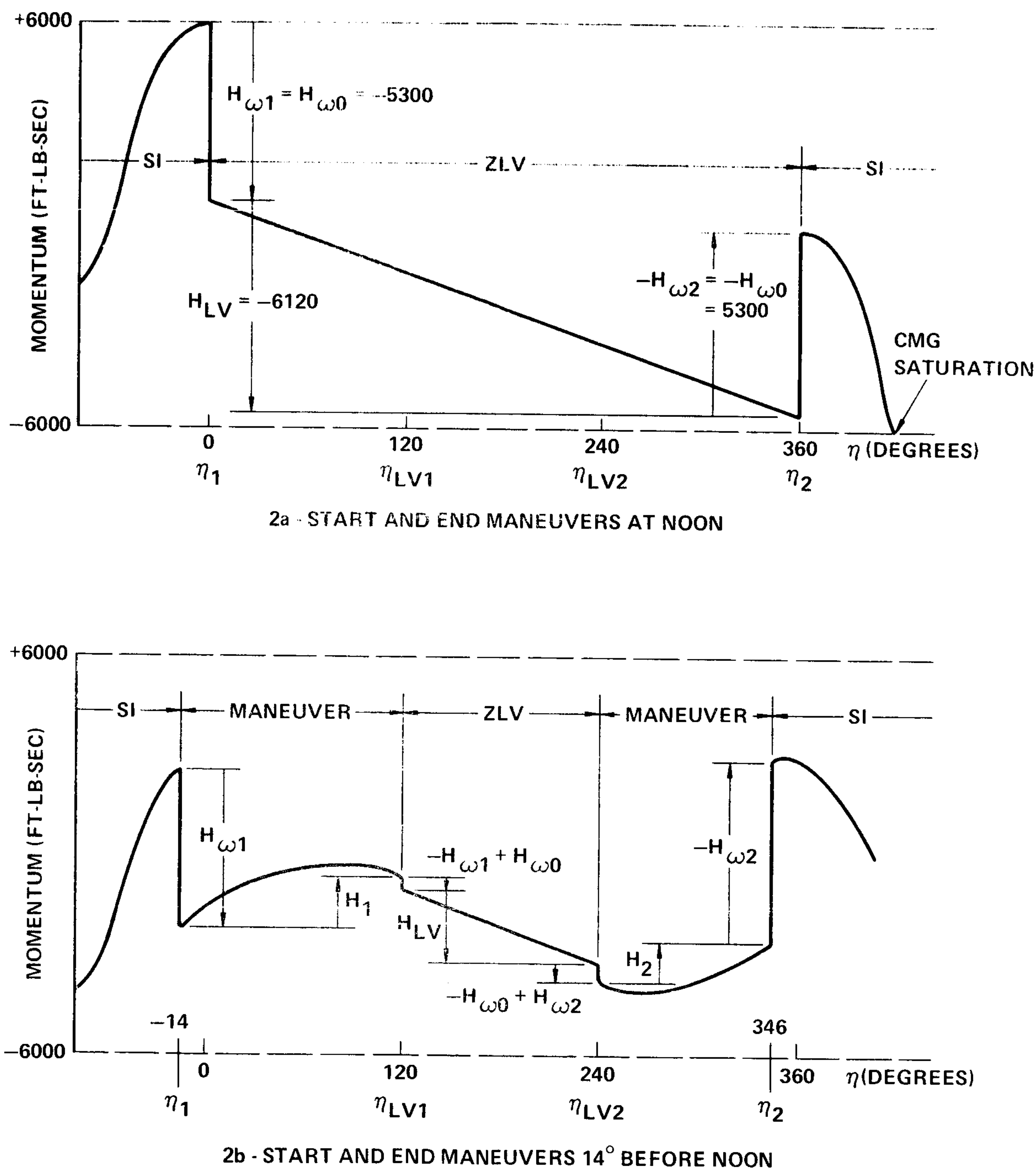

FIGURE 2 - CMG Y AXIS MOMENTUM PROFILE DURING A 120° ZLV PASS CENTERED AT MIDNIGHT

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